Draft version March 28, 2017
Typeset using LaTeX **manuscript** style in AASTeX61

RADIAL VARIATIONS OF OUTWARD AND INWARD ALFVÉNIC FLUCTUATIONS BASED ON ULYSSES OBSERVATIONS

L. Yang,[1, 2, *] L. C. Lee,[3, 4] J. P. Li,[5] Q. Y. Luo,[1] C. L. Kuo,[3] J. K. Shi,[2] and D. J. Wu[1]

[1] *CAS Key Laboratory of Planetary Sciences, Purple Mountain Observatory, CAS, Nanjing 210008, China*
[2] *State Key Laboratory of Space Weather, National Space Science Center, CAS, Beijing 100190, China*
[3] *Institute of Space Science, National Central University, Jhongli 320, Taiwan*
[4] *Institute of Earth Sciences, Academia Sinica, Taipei 11529, Taiwan*
[5] *Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China*

ABSTRACT

Ulysses magnetic and plasma data are used to study hourly-scale Alfvénic fluctuations in the solar polar wind. The calculated energy ratio $R^2_{v_A}$(cal) of inward to outward Alfvén waves is obtained from the observed Walén slope through an analytical expression, and the observed $R^2_{v_A}$(obs) is based on a direct decomposition of original Alfvénic fluctuations into outward- and inward-propagating Alfvén waves. The radial variation of $R^2_{v_A}$(cal) shows a monotonically increasing trend with heliocentric distance r, implying the increasing local generation or contribution of inward Alfvén waves. The contribution is also shown by the radial increase in the occurrence of dominant inward fluctuations. We further pointed out a higher occurrence ($\sim$ 83% of a day in average) of dominant outward Alfvénic fluctuations in the solar wind than previously estimated. Since $R^2_{v_A}$(cal) is more accurate than $R^2_{v_A}$(obs) in the measurement of the energy ratio for dominant outward fluctuations, the values of $R^2_{v_A}$(cal) in our results are likely more realistic in the solar wind than previously estimated and

Corresponding author: L. Yang
ylei@pmo.ac.cn

than $R^2_{v_A}$(obs) in our results. The duration ratio R_T of dominant inward to all Alfvénic fluctuations increases monotonically with r, and is about two or more times that from *Voyager 2* observations at $r \geq 4$ AU. Finally, from the variation trend in our results, a higher (lower) occurrence rate is expected at $r < 1$ AU ($r > 4$ AU) for dominant outward Alfvénic fluctuations, and opposite variations are expected for dominant inward fluctuations. Simultaneously, $R^2_{v_A}$(cal) and R_T will be expected to be smaller at $r < 1$ AU and larger at $r > 4$ AU. These results reveal new qualitative and quantitative features of Alfvénic fluctuations therein compared with previous studies and put constraints on modelling the variation of solar wind fluctuations.

Keywords: magnetohydrodynamics (MHD) — methods: analytical — plasmas — solar wind — wave

* Correspondence should be addressed to L.Y.

1. INTRODUCTION

Alfvén waves, as a type of magnetohydrodynamic wave in which ions oscillate in response to a restoring force provided by an effective tension on the magnetic field lines (Alfvén 1942), have been extensively investigated in the solar wind context (e.g., Belcher & Davis 1971; Yang & Chao 2013 for a review) and have a significant contribution to the solar wind acceleration and coronal heating (e.g., van der Holst et al. 2014, and references therein). Impressive advances have been made in both relevant observations and the theory of Alfvén waves.

Outward-propagating (away from the Sun) Alfvén waves are often observed in the solar wind since the end of 1960s (e.g., Belcher et al. 1969; Daily 1973; Burlaga & Turner 1976; Denskat & Neubauer 1982; Riley et al. 1996), and inward-propagating (toward the Sun) ones are usually mentioned without providing specific observations. With the development of satellite technology providing higher time-resolution plasma and magnetic field data, both case and statistical studies clearly show the relatively rare existence of inward Alfvén waves at 1 AU and beyond (i.e., Belcher & Davis 1971; Roberts et al. 1987a,b; Bavassano & Bruno 1989; Gosling et al. 2009, 2011; Wang et al. 2015; He et al. 2015; Li et al. 2016, etc). When the solar wind expands, both outward and inward Alfvén waves may meet each other, and the superposition of both waves can cause the subunity of Walén slope when Alfvénic fluctuations observed in the solar wind are assumed to be a mixture of both waves with opposite propagation directions in the wind plasma frame of reference (i.e., D'Amicis & Bruno 2015). This superposition model of inward and outward Alfvén waves is confirmed by the observational evidence from the *Wind* data (Yang et al. 2016).

Owing to important contributions to the dynamics of the solar wind (Alazraki & Couturier 1971; Belcher 1971; Hollweg 1973a,b), it is necessary to study the Alfvén wave variation/evolution in the solar wind at various heliocentric distances (Belcher & Davis 1971; Hollweg 1974; Roberts et al. 1987a). With increasing heliocentric distance away from the Sun, the Alfvén wave period was found to become shorter (Bruno et al. 1985), and that both the normalized cross helicity and the Alfvén ratio (i.e., the ratio of kinetic to magnetic energy of the fluctuation) decrease (e.g., Bavassano et al. 1982; Matthaeus & Goldstein 1982; Bruno et al. 1985; Bruno & Dobrowolny 1986; Roberts et al.

1987b,a, 1990; Grappin et al. 1990; Marsch & Tu 1990; Matthaeus et al. 2004), implying an evolution toward a less purely Alfvénic state in the outer heliosphere. Such decreases may be caused by the gradual increase in the occurrence of inward-propagating Alfvén waves (Roberts et al. 1987a,b) and the radial expansion of the solar wind (Whang 1973; Hollweg 1974). Helios 1 and 2 observations show the agreement of the radial evolution of the wave amplitudes with saturated waves (i.e., with a constant energy density ratio of the wave to the background magnetic field) rather than with undamped ones (i.e., the wave energy is conserved) in 0.41–0.65 AU (Villante 1980).

These results mentioned above show that the contribution of the Alfvén waves to the energetics of the solar wind may be greater than previously estimated. The presence of the two opposite direction waves could facilitate the development of nonlinear interactions (e.g., Dobrowolny et al. 1980) for the dynamical evolution of the MHD turbulence (Bruno & Carbone 2013) and be responsible for the decreases in the normalized cross helicity of Alfvénic fluctuations with increasing heliocentric distance (e.g., Matthaeus & Goldstein 1982; Roberts et al. 1987a,b; Grappin & Velli 1996; Bavassano et al. 2000a; Matthaeus et al. 2004). The interaction between both Alfvén waves is also believed to be an important source for solar wind plasma heating (van der Holst et al. 2014).

For the first time, the *Ulysses* mission measured directly the solar wind plasma and field properties in the polar region, which are different from the low-latitude (or the ecliptic) solar wind flows (i.e., Horbury et al. 1995; Goldstein et al. 1995; Smith et al. 1995; Tsurutani et al. 1996; Smith et al. 1997; McComas et al. 2000; Ebert et al. 2013). Its observations of Alfvénic fluctuations show that the wave properties in the polar wind seem to be determined mainly by the heliocentric distance rather than by the heliographic latitude (e.g., Goldstein et al. 1995; Horbury et al. 1995). With the solar heliocentric distance, the anisotropy of the magnetic fluctuations increases but the Alfvénicity decreases (Neugebauer 2004). A systematic study (Bavassano et al. 2000b) on the radial variation of outward- and inward-propagating Alfvénic fluctuations in the polar wind indicates that inside ~ 2.5 AU, the outward-propagating fluctuations decrease faster than the inward ones but beyond $\sim$ 2.5 AU, the radial gradient of inward ones increase faster. This result implies different radial regimes of Alfvénic fluctuations at different distances, that is, the radial variation of Alfvénic fluctuations are

radially dependent. The features of dominant outward and dominant inward Alfvénic fluctuations put a constraint on modelling the wave/turbulence variation/evolution in the solar wind.

Recently, we provided direct observational evidence that the superposition of inward- and outward-propagating Alfvén waves can cause the subunity of Walén slope, and obtain an analytical relation between the Walén slope and the amplitude ratio of inward to outward waves (Yang et al. 2016). The Walén slope is obtained using the CHYL method (Chao et al. 2014), which can better quantitatively estimate the Walén slope of Alfvénic fluctuations in the solar wind.

In the present paper, the term “Alfvén wave” is adopted to depict the plasma and related magnetic fluctuations with a Walén slope $|R_W| = 1$. This kind of waves is also called pure (unidirectionally propagating) Alfvén waves. Another term “Alfvénic fluctuation” is used to describe propagating fluctuations with $|R_W| < 1$ in order to differentiate it from the term “Alfvén wave” . This kind of fluctuations can be interpreted as a mixture of outward- and inward-propagating Alfvén waves (Yang et al. 2016), based on which the Alfvénic fluctuations can be classified into dominant inward- and dominant outward-propagating ones if the amplitude ratio R_{v_A} of inward to outward Alfvén waves is larger or smaller than 1. In order to be consistent with previous studies, the term “Alfvén wave” is still used for convenience in this section although it is more accurate to use “Alfvénic fluctuations” to describe the observed plasma and magnetic variations from a physical point of view. In this paper, the Ulysses magnetic and plasma data are used to examine the radial variations of outward- and inward-propagating Alfvénic fluctuations in the solar wind.

2. MODEL

Yang et al. (2016) shows that the amplitude ratio R_{v_A} of the inward to outward Alfvén waves can be related to the Walén slope R_W by the following equations in the RTN coordinates,

$$R_{v_A}(\mathrm{cal}) = \frac{1 + R_W}{1 - R_W} \text{ (for } B_R > 0) \tag{1}$$

and

$$R_{v_A}(\mathrm{cal}) = \frac{1 - R_W}{1 + R_W} \text{ (for } B_R < 0). \tag{2}$$

The Walén slope R_W is calculated from $\Delta\mathbf{V} = R_W \Delta\mathbf{V}_A$, and equals ± 1 for pure (unidirectionally propagating) Alfvén waves. Here $\Delta\mathbf{V}$ and $\Delta\mathbf{V}_A$ are the time difference of the bulk and Alfvén velocities from satellite observations, which was proposed by Chao et al. (2014, the CHYL method hereafter). This method can better quantitatively estimate the Walén slope of Alfvénic fluctuations in the solar wind. From the amplitude ratio, $R_{v_A}(\text{cal})$, it is easy to get the related energy ratio of inward to outward Alfvén waves, i.e., $e_-/e_+ = R_{v_A}(\text{cal})^2$. Note that the calculated ratio $R_{v_A}(\text{cal})$ is obtained from R_W, which is determined by the observed $\Delta\mathbf{V}$ and $\Delta\mathbf{V}_A$.

We define the ratio $R_{v_A}(\text{obs})$, which is directly calculated from satellite observations, as

$$R_{v_A}(\text{obs}) \equiv \frac{\text{rms of } \Delta\mathbf{V}_{\text{Ain}}}{\text{rms of } \Delta\mathbf{V}_{\text{Aout}}}. \tag{3}$$

Here rms means the root mean square values for $\Delta\mathbf{V}_{\text{Ain}}$ and $\Delta\mathbf{V}_{\text{Aout}}$,

$$\Delta\mathbf{V}_{\text{Ain}} = \Delta\mathbf{V}_{\text{in}} = \frac{\Delta\mathbf{V}_{\text{A}} + \Delta\mathbf{V}}{2}, \quad \Delta\mathbf{V}_{\text{Aout}} = -\Delta\mathbf{V}_{\text{out}} = \frac{\Delta\mathbf{V}_{\text{A}} - \Delta\mathbf{V}}{2} \quad (\text{for } B_R > 0) \tag{4}$$

and

$$\Delta\mathbf{V}_{\text{Aout}} = \Delta\mathbf{V}_{\text{out}} = \frac{\Delta\mathbf{V}_{\text{A}} + \Delta\mathbf{V}}{2}, \quad \Delta\mathbf{V}_{\text{Ain}} = -\Delta\mathbf{V}_{\text{in}} = \frac{\Delta\mathbf{V}_{\text{A}} - \Delta\mathbf{V}}{2} \quad (\text{for } B_R < 0). \tag{5}$$

The subscripts "in" and "out" denote inward and outward wave propagation directions.

For a complete description of the superposition model of inward- to outward-propagating Alfvén waves in the solar wind, readers are referred to our recent work on this topic (Yang et al. 2016). The work presented observational evidence for the relationship between Walén slope, R_W, and the amplitude ratio, $R_{v_A}(\text{cal})$, of inward to outward Alfvén waves to explain the subunity Walén slope of Alfvénic fluctuations in the solar wind, and showed that the values of $R_{v_A}(\text{cal})$ are closer to true values and smaller than $R_{v_A}(\text{obs})$ for dominant outward-propagating Alfvénic fluctuations.

3. DATA AND METHODOLOGY

The plasma and magnetic field data of Ulysses mission (Wenzel et al. 1992) will be used to study the radial variation of Alfvénic fluctuations in the solar wind. The time resolution of plasma data (including the bulk velocity, the proton number density) is either 4 or 8 minutes due to different operating modes. The magnetic field data are 1-minute averaged.

We follow the same procedure of Bavassano et al. (2000b) to select the events for Alfvénic fluctuations in order to compare our results with theirs directly. Firstly, averages over 4 or 8 minutes of the magnetic field data are taken to get the corresponding magnetic vector with respect to the time of the plasma data. The combined magnetic and plasma data give the Alfvén velocity $\mathbf{V}_A$ for further selecting Alfvénic events.

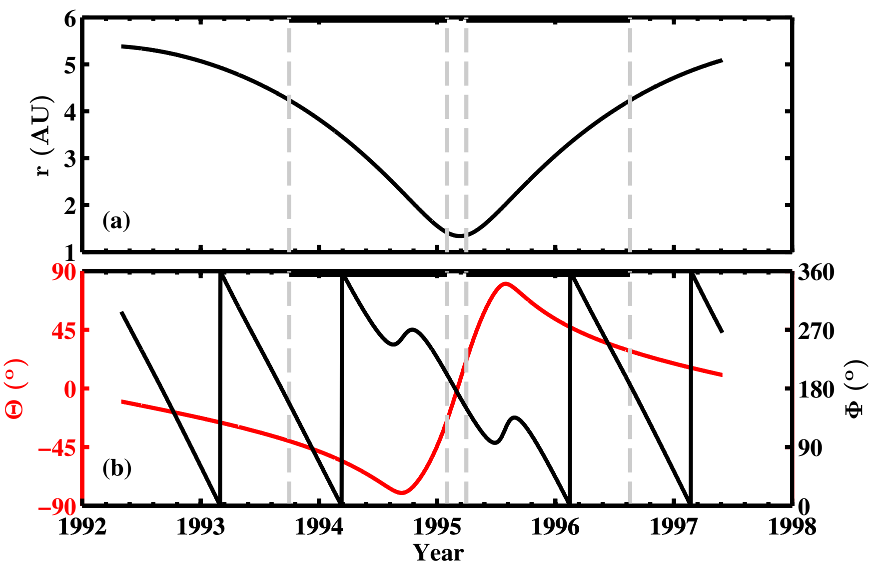

Figure 1. The Ulysses heliocentric distance (r), latitude (Θ), and longitude (Φ) in an inertial heliographic coordinate system versus time from mid 1992 to mid 1997. Thick bars indicate the polar wind regions to be studied. Same as part of Figure 1 in Bavassano et al. (2000b).

Secondly, relatively homogeneous and steady flow regions are selected on a daily basis (i.e., 24 hour duration). To reduce the effects of nonsteady plasma flows and other processes (e.g., shear and compression effects) in the solar wind, the rejected hourly data intervals are those with large changes in the number density N or the magnetic field magnitude B (i.e., the related relative standard deviations of N and B for each day are above given thresholds). The selection can effectively exclude the strongest disturbances, ensuring that the selected sample is more likely Alfvénic than the original one. Although there is no constraint on the velocity-magnetic field correlation in Bavassano et al. (2000b), we have checked that if we only select the events with a correlation coefficient ≥ 0.6, the

results will not change dramatically. The selected two periods in polar regions are represented in Figure 1 by thick bars and will be used for further analysis of Alfvénic fluctuations therein. The left bar denotes the southern passage (the heliographic latitude $\Theta < 0$), and the right bar denotes the northern one ($\Theta > 0$). For more detailed information of the data selection for the two periods, interested readers are referred to Bavassano et al. (2000b).

Thirdly, averages over 0.1 AU of the hourly means of R_{v_A} or e_-/e_+ are used to study the radial variation of the Alfvénic fluctuations. The investigated heliocentric distance is in the range of 1.4–4.3 AU. Owing to little difference of solar wind fluctuation properties between the northern and southern hemispheres (i.e., Bavassano et al. 1999, 2000b), we will analyse together the observations from both hemispheres.

Finally, in addition to the above criteria mentioned by Bavassano et al. (2000b), one more criterion is adopted in the present paper, that is, only cases with $0 \leq R_{v_A} \leq 7$ are selected based on the parameters from Yang et al. (2016). The number of other cases are too small ($\sim 3\%$ of all events selected from the method of Bavassano et al. (2000b)) to obviously affect the statistical results although some subtle qualitative difference does exist. Here it should be noted that, in most cases, we use the mean value of a specific parameter of interest to discuss the radial variation of Alfvénic fluctuations in the solar wind, unless otherwise stated.

4. RESULTS

The selected two periods of *Ulysses* observations are 1993/10/01-1995/01/31 and 1995/04/01/–1996/08/19 when the solar wind was relatively homogeneous and steady. The corresponding heliocentric distance is 1.4–4.3 AU. One event duration is one hour. The total number of selected events for further analysis is 21739. The number ratio of dominant inward to dominant outward Alfvénic fluctuations is about 11.3% for the whole sample, that is, the fraction of the dominant fluctuations accounts for $\sim 10.2\%$ of the total (outward and inward) Alfvénic duration. For Alfvén wave events in the solar wind, we have $|R_W| \leq 1$ and $R_{v_A} \geq 0$ (Yang et al. 2016).

Two typical events from *Ulysses* observations are shown in Figure 2 for dominant (a) outward and (b) inward Alfvénic fluctuations in the solar polar winds, with the wave amplitude ratio $R_{v_A} < 1$ and

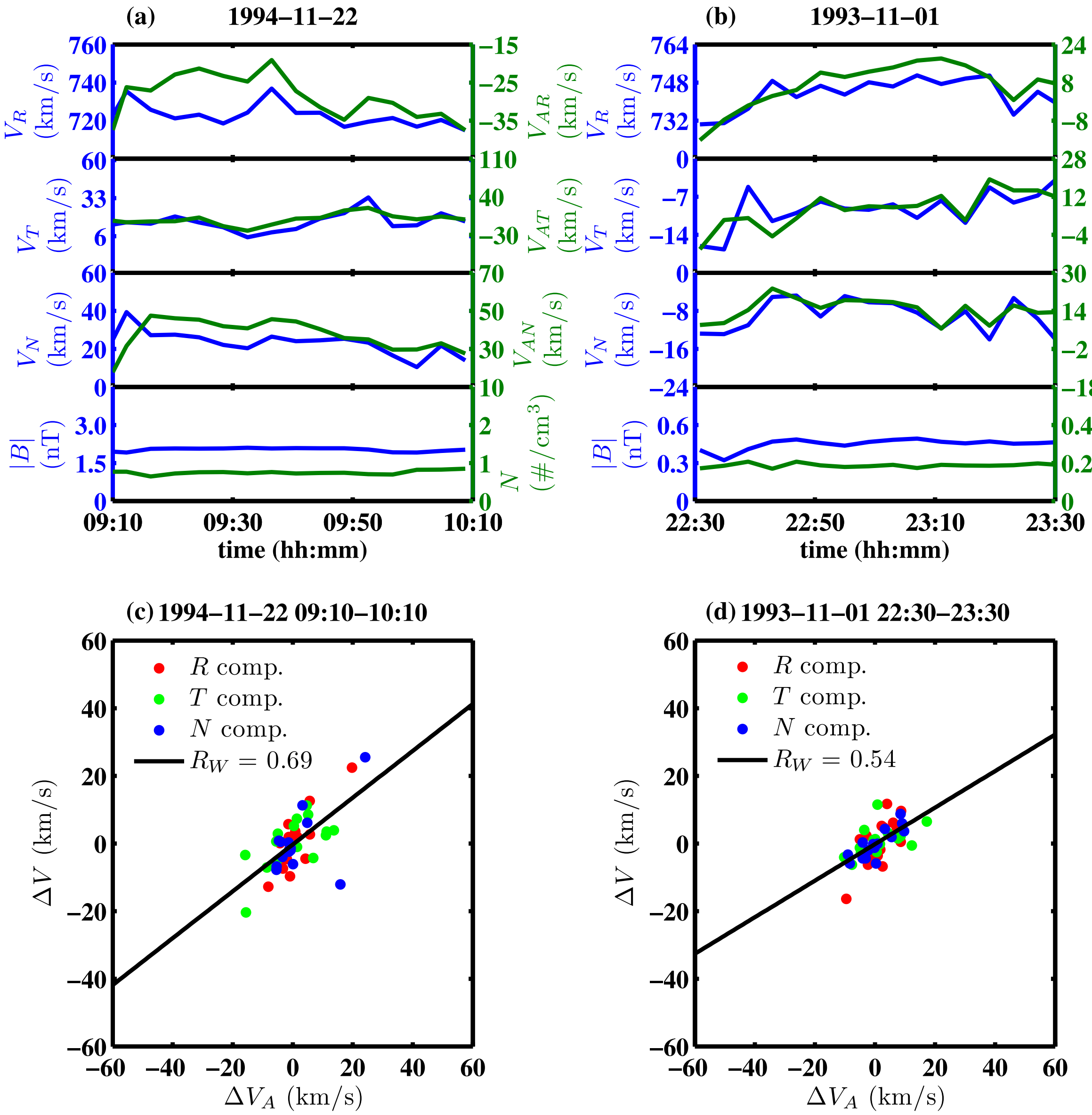

Figure 2. Solar wind velocity (V_R, V_T, V_N), Alfvén velocity (V_{AR}, V_{AT}, V_{AN}), the magnetic field intensity ($|\mathbf{B}|$), and proton number density (N) in Radial-Tangential-Normal (RTN) coordinates for dominant (a) outward and (b) inward Alfvénic fluctuations observed by *Ulysses*. Related differences in the velocity ($\Delta\mathbf{V}$) vs. those in Alfvén velocity ($\Delta\mathbf{V}_A$) are plotted in panels (c) and (d), respectively.

$R_{v_A} > 1$, respectively. They have common characteristics of Alfvén waves, i.e., relatively constant $|\mathbf{B}|$ and density N and well correlated $\mathbf{V}$ and $\mathbf{B}$. The related Walén slopes are subunity (i.e., $|R_W| < 1$)

for all three components of **V** and **B**, which can be explained by the superposition of outward- and inward-propagating Alfvén waves with an amplitude ratio R_{v_A} calculated from Equations (1) or (2).

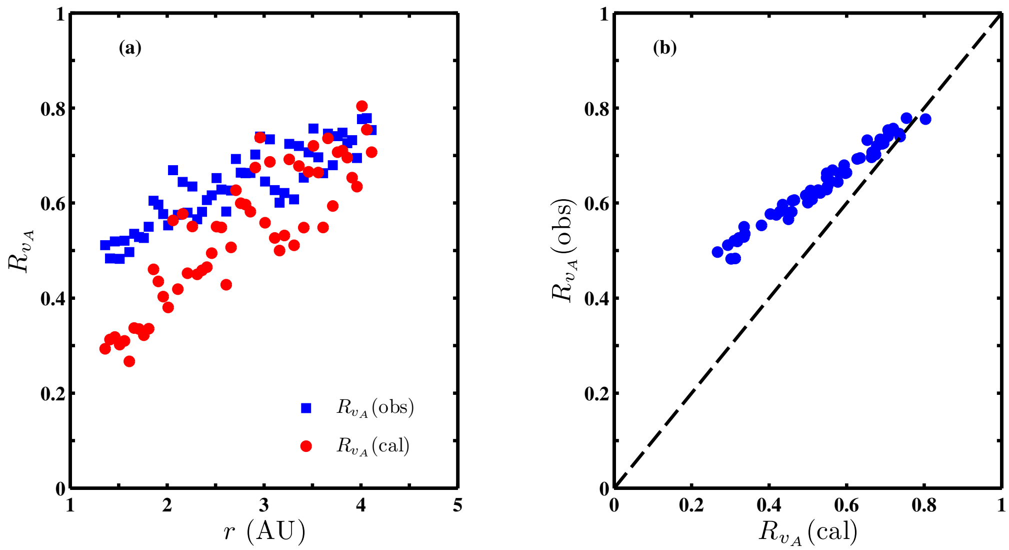

Figure 3. (a) Radial variation of the amplitude ratio (R_{v_A}) of inward to outward Alfvén waves and (b) scatter plot of observed R_{v_A}(obs) vs. calculated R_{v_A}(cal) from *Ulysses* observations in the selected time periods shown in Figure 1.

Figure 3 shows that R_{v_A}(obs) is larger than R_{v_A}(cal) when inward Alfvén waves are not dominant (e.g., R_{v_A}(cal) ≤ 0.5) at heliocentric distances smaller than ~ 3 AU, and close to R_{v_A}(cal) when both wave amplitudes are comparable (e.g., R_{v_A}(cal) > 0.5) at a larger distance (≥ 3 AU). This result is consistent with Yang et al. (2016). They showed that R_{v_A}(obs) $\geq R_{v_A}$(cal) for dominant outward Alfvénic fluctuations due to the presence of non-Alfvénic noise and R_{v_A}(cal) is closer to the true value of R_{v_A} than R_{v_A}(obs). Both R_{v_A}(cal) and R_{v_A}(obs) increases with heliocentric distance r, indicating the gradually increasing contribution or generation of inward Alfvén waves through some instabilities or other physical mechanisms. The properties of the variation of R_{v_A} are consistent with previous studies on this topic (e.g., Roberts et al. 1987a,b; Bavassano et al. 2000b; Li et al. 2016).

The radial variation of the energy ratio $R^2_{v_A}$(obs) shown in Figure 4(a) is similar to the results of Bavassano et al. (2000b), which confirms the validity of the application of the CHYL method (Chao et al. 2014) in the studies for identifying Alfvénic fluctuations in the solar wind. As mentioned

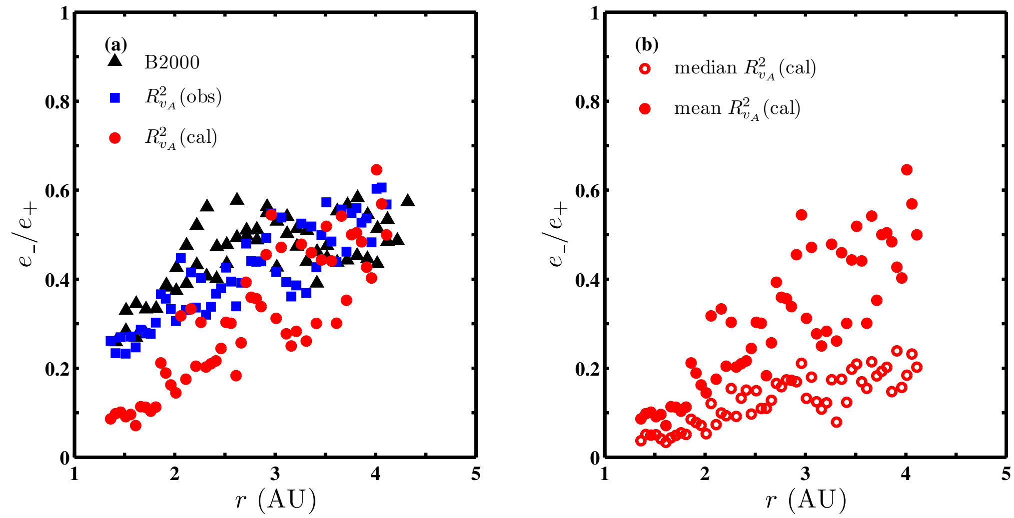

Figure 4. Radial variations of (a) energy ratio ($e_-/e_+ = R^2_{v_A}$) of inward to outward Alfvén waves from Bavassano et al. (2000b, denoted by B2000), observed $R^2_{v_A}$(obs), calculated $R^2_{v_A}$(cal), and (b) the median and the mean of $R^2_{v_A}$(cal).

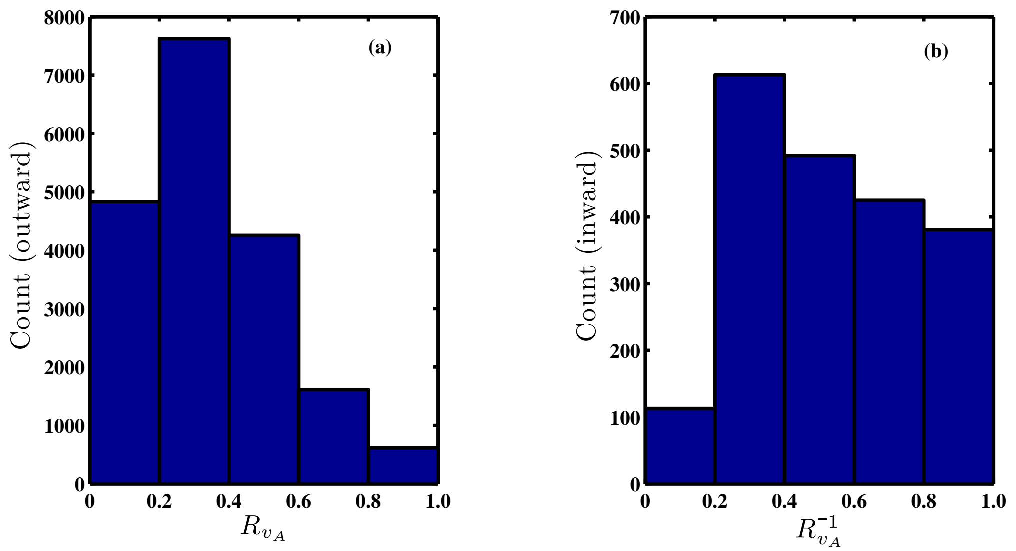

Figure 5. Distributions of R_{v_A} and $R^{-1}_{v_A}$ for dominant (a) outward and (b) inward Alfvénic fluctuations, where R_{v_A} is the amplitude ratio of inward to outward Alfvén waves.

earlier, R_{v_A}(cal), derived from observed Walén slope based on Equation (1) or (2), is more accurate than R_{v_A}(obs). The values of $R^2_{v_A}$(cal) can be half or less of those by Bavassano et al. (2000b) or $R^2_{v_A}$(obs) obtained here at smaller heliocentric distances (< 3 AU), and closer to or approaches

the previous results at larger heliocentric distances (> 3 AU). The features for this difference are due to different radial behaviour of the energy ratio $R^2_{v_A}$ (or e_-/e_+) presented by the two studies. Bavassano et al. (2000b) found two different regimes of the Alfvénic fluctuation variations at different heliocentric distances, that is, inside about 2.5 AU the energy ratio e_-/e_+ exists a rising trend with the heliocentric distance r, and beyond the distance the ratio becomes almost constant (~ 0.5) with r. However, in the present work, the variation of wave energy ratio $R^2_{v_A}$(cal) (or e_-/e_+) shows an obvious monotonically increasing trend with r. The basic reason for the different trends is that we use Equations (1) or (2) to get the wave energy ratio $R^2_{v_A}$ (i.e., $R^2_{v_A}$(cal)) while Bavassano et al. (2000b) used the perturbed quantities for calculating the wave energy ratio, similar to $R^2_{v_A}$(obs). It has been shown that $R^2_{v_A}$(cal) is more accurate than $R^2_{v_A}$(obs) (Yang et al. 2016). The radial variation of $R^2_{v_A}$(obs) in Figure 4(a) is similar to those by Bavassano et al. (2000b). It is likely that the values of $R^2_{v_A}$(cal) in our results are closer to realistic physical processes in the solar wind than those of Bavassano et al. (2000b) and those of $R^2_{v_A}$(obs) in our results.

The radial variations of the median and the mean of $R^2_{v_A}$(cal) in Figure 4(b) are different at different heliocentric distances r. Inside $\sim$ 3 AU, both radial variations of $R^2_{v_A}$(cal) are similar, but in the larger distances ($r > 3$ AU), the difference between the median and the mean is increasing with r. The mean $R^2_{v_A}$(cal) can be two times or more that of the relevant median at about 4 AU, indicating the existence of some extremely large values of $R^2_{v_A}$(cal) and hence the existence of purely inward-propagating Alfvén waves. Both median and mean show an increasing trend with r, and the mean values have a steeper rate with r than the median ones. The increase in $R^2_{v_A}$(cal) with r implies the increasing contribution beyond the observed site or the local generation of inward Alfvén waves. In addition, the distribution of the median $R^2_{v_A}$(cal) with r is more compact than that of the relevant mean.

Figure 5 shows the count of dominant outward Alfvénic fluctuations and the count of dominant inward ones as a function of R_{v_A} and $R^{-1}_{v_A}$, respectively. The dominant outward (inward) fluctuation distribution in Figure 5(a) (Figure 5(b)) peaks at the range of R_{v_A} ($R^{-1}_{v_A}$) from 0.2 to 0.4, which means that the amplitude of inward (outward) Alfvén waves accounts for 20–40% of that of outward (inward)

waves and that the peak fraction is 40.3% (30.3%) of all outward (inward) fluctuation events. The count then gradually decreases with R_{v_A} in both dominant inward and outward fluctuation events. Besides, the distributions of R_{v_A} and $R_{v_A}^{-1}$ are different for the two kinds of fluctuations, respectively. The count of highly pure Alfvén wave events ($0 \leq R_{v_A} < 0.2$) with an outward propagation sense in Figure 5(a) accounts for 25.5% of all the dominant outward fluctuation events, while the count of highly pure Alfvén wave events ($0 \leq R_{v_A}^{-1} < 0.2$) with an inward one in Figure 5(b) accounts for only 5.6% of all the dominant inward fluctuation events. Similarly, for a comparable amplitude ratio, the dominant outward fluctuation events with $0.8 < R_{v_A} \leq 1.0$ account for only 3.2% of all the dominant outward fluctuation events, but the dominant inward fluctuation events with $0.8 < R_{v_A}^{-1} \leq 1.0$ account for 18.8% of all the dominant inward fluctuation events. The features of these distributions may relate to the physical properties of the outward and inward Alfvénic fluctuations in the solar wind.

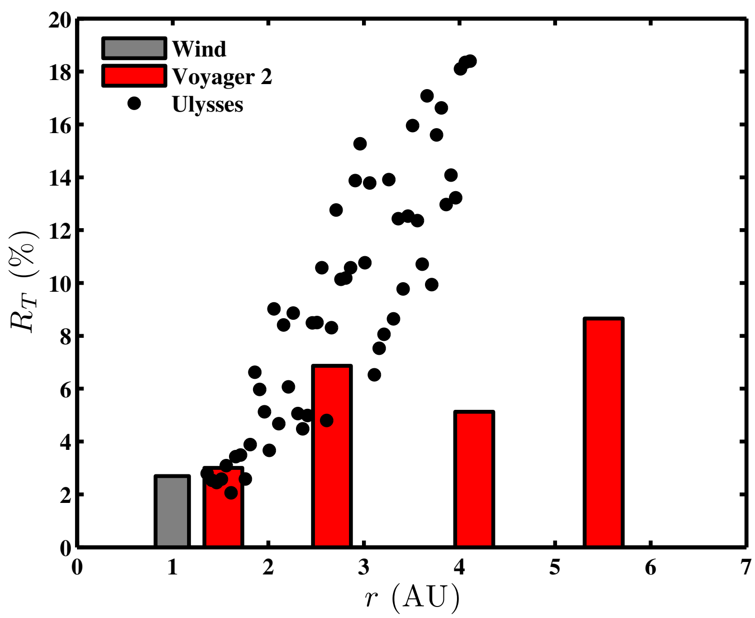

Figure 6. Radial variations of the duration ratio (R_T) of dominant inward to all Alfvénic fluctuations from *Ulysses*, *Wind*, and *Voyager 2* observations. The *Wind* and *Voyager 2* results are taken from Li et al. (2016).

Ulysses observations of Alfvénic fluctuations in Figure 6 indicate that the duration ratio R_T of dominant inward to all (outward and inward) Alfvénic fluctuations increases monotonically with

heliocentric distance r, showing a different variation trend from *Wind* and *Voyager 2* observations (Li et al. 2016). At smaller heliocentric distances ($\leq$ 3 AU), R_T based on *Ulysses* observations is similar to that from *Wind* and *Voyager 2* results, but at larger heliocentric distances ($\geq$ 4 AU), the variation of R_T with r based on *Ulysses* observations is about two or more times that from *Voyager 2* observations.

There are two possible reasons that may have contributed to the difference between the results from *Ulysses* and *Voyager 2* at larger heliocentric distances. Firstly, *Voyager 2* in the investigated period from 1977 to 1979 was in the ecliptic plane inside 6 AU, while *Ulysses* was mainly in the polar wind regions for selected periods (see Figure 1). The occurrence of outward and inward Alfvénic fluctuations may be different in the polar and ecliptic regions due to different evolution mechanisms of solar wind fluctuations or the interactions with different magnetic structures therein. Secondly, different phases of a solar cycle can also make the difference. The time periods selected for *Voyager 2* were in the rising phase of one solar cycle, but those selected for *Ulysses* were in another solar cycle's declining phase. Solar activity levels of different phases in a cycle are different, which may give rise to the solar wind with different populations of dominant outward and inward Alfvénic fluctuations. Further studies on this difference are needed in the future to clarify these issues. Here we only present new observational features of radial variation of Alfvénic fluctuations in the solar wind based on the Walén slope (i.e., Equations (1) and (2)).

The occurrence rates of dominant inward and outward Alfvénic events with heliocentric distance r show different variation trends in Figure 7. The occurrence of dominant outward fluctuation events monotonically decreases with r but that of dominant inward ones monotonically increases with r, implying the increasing local generation of inward-propagating Alfvén waves, mixing with some dominant outward-propagating ones. The inward-propagating waves may be excited by the reflection or damping of outward Alfvén waves via nonlinear interactions with static magnetic structures or some plasma parametric instabilities in the solar wind. Another point is that, in the heliocentric distance of 1.4–2 AU, the occurrence rate of dominant outward fluctuation events can be at least

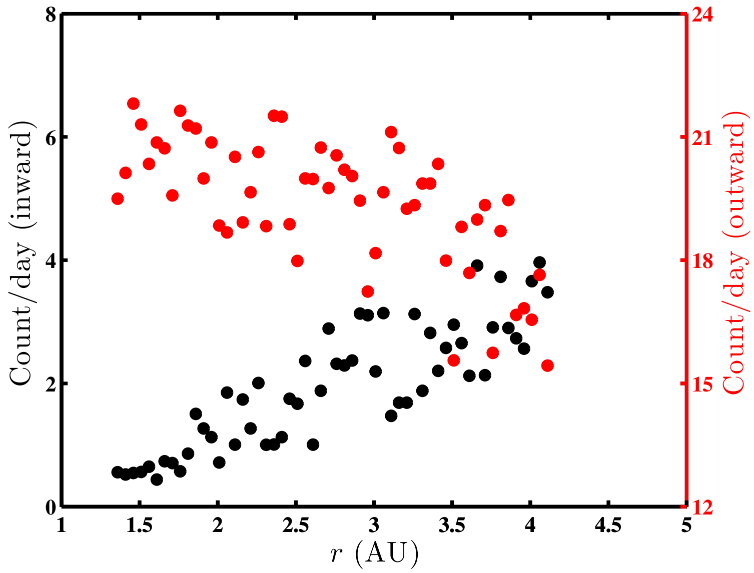

Figure 7. Occurrence rates of dominant inward (black dots) and outward (red dots) Alfvénic fluctuations observed by Ulysses at different heliocentric distances.

3.9 times that of inward ones, consistent with the predominance of previously observed outward-propagating Alfvénic fluctuations in the solar wind (see the review by Yang & Chao 2013).

In Figure 7, the duration of one count (or one event) is 1 hour. The occurrence rate of dominant outward fluctuation events is estimated to be ~ 20 per day near 1 AU, accounting for 83% of a day in average, comparable to 75% estimated by Denskat et al. (1981), higher than 55% estimated by Belcher & Davis (1971), 39% by Denskat & Burlaga (1977), and 64.8% by Shi et al. (2015), and much higher than 22% by Roberts et al. (1987b) and 5%–10% by Riley et al. (1996) in different samples from different satellite observations. These different occurrence rates (or time fractions) of Alfvénic fluctuations can be affected by various factors such as the event duration selected, the selection criteria of Alfvénic fluctuations, and the instrument sampling rate. These factors are considered to be carried out in our future work. Our study shows that the occurrence of Alfvénic fluctuations in the solar wind is higher than previously estimated.

From the trend in Figure 7, it is expected that dominant outward Alfvénic fluctuations will have a higher occurrence rate at a heliocentric distance $r < 1$ AU and a lower occurrence rate at $r > 4$ AU. For dominant inward Alfvénic fluctuations, the opposite variation of the relevant occurrence rate is

expected. Accordingly the amplitude ratio or the energy ratio of inward to outward Alfvén waves will be expected to become smaller at $r < 1$ AU and larger at $r > 4$ AU (see Figures 3 and 4 for the variation trend). And so does the duration ratio of inward Alfvénic fluctuations to all Alfvénic fluctuations in Figure 6.

5. SUMMARY AND CONCLUSIONS

Using Walén analysis for the superposition of outward- and inward-propagating Alfvén waves (Yang et al. 2016), we investigated the radial variations of dominant outward and inward Alfvénic fluctuations observed by *Ulysses* in the heliocentric distance of 1.4–4.3 AU. The main results can be summarized as follows.

1. For dominant outward Alfvénic fluctuations, the observed amplitude ratio R_{v_A}(obs) of inward to outward waves from direct decompositions is larger than or comparable to R_{v_A}(cal) calculated from Walén slope in Equations (1) or (2), which is expected by Yang et al. (2016). The increases in both R_{v_A}(cal) and R_{v_A}(obs) with heliocentric distance r imply the gradually increasing contribution or generation of inward Alfvén waves via plasma instabilities or some other physical mechanisms, consistent with previous observations.

2. The similarity of the radial variation of the energy ratio $R^2_{v_A}$(obs) (or e_-/e_+) (Figure 4(a)) between our work and Bavassano et al. (2000b) confirms the validity of the CHYL method (Chao et al. 2014) applied for identifying Alfvénic fluctuations in the solar wind. But R_{v_A}(cal), derived from Equations (1) or (2), is closer to the true value of R_{v_A} than R_{v_A}(obs) (Yang et al. 2016). The values of $R^2_{v_A}$(cal) can be half or less of those obtained by Bavassano et al. (2000b) or $R^2_{v_A}$(obs) at $r < 3$ AU, and closer to or approaches their results at $r > 3$ AU. Another important point in the present work is that $R^2_{v_A}$(cal) monotonically increases with r. Since R_{v_A}(cal) is more accurate than R_{v_A}(obs) in the measurement of the amplitude ratio, our results may be considered more realistic than those of Bavassano et al. (2000b).

3. The peak in the distribution of R_{v_A} ($R^{-1}_{v_A}$) for dominant outward (inward) fluctuations in Figure 5(a) (Figure 5(b)) suggests that the amplitude of inward (outward) Alfvén waves account for

20–40% of that of outward (inward) waves, which may be relevant to various physical properties of Alfvénic fluctuations in the solar wind.

4. In comparison with *Wind* and *Voyager 2* observations (Li et al. 2016), the duration ratio R_T of dominant inward to all Alfvénic fluctuations increases monotonically with r, and is about two or more times that from *Voyager 2* observations at $r \geq 4$ AU (see Figure 6). These differences may be caused by different spacecraft locations and different solar activity levels.

5. The occurrence rate of dominant outward fluctuation events is ~ 20 per day near 1 AU, accounting for 83% of a day in average (Figure 7), higher than previously estimated values due to various factors such as the event duration selected, the selection criteria of Alfvénic fluctuations, and the instrument sampling rate of different satellites.

Finally, we expect that dominant outward Alfvénic fluctuations will have a higher occurrence rate at $r < 1$ AU and a lower occurrence rate at $r > 4$ AU. For dominant inward Alfvénic fluctuations, we would expect the opposite variations. Similarly, the amplitude ratio R_{v_A} and the duration ratio R_T will be anticipated to be smaller at $r < 1$ AU and larger at $r > 4$ AU (Figures 3 and 6). These results have important implications for the variations of solar wind fluctuations and reveal several new qualitative and quantitative features of Alfvénic fluctuations therein compared with previous studies.

This work was supported in part by the Specialized Research Fund for State Key Laboratories and NSFC (grant 41531071). L.C.L. was supported by NSC of Taiwan (grant MOST 104-2111-M-001-003-MY2), Q.Y.L. by NSFC (grant 11173061), and C.L.K. by NSC of Taiwan (grant MOST 105-2816-M-008-002). The authors thank the data providers of *Ulysses* and NASA's CDAWeb for making these data available.

REFERENCES

Alazraki, G., & Couturier, P. 1971, A&A, 13, 380

Alfvén, H. 1942, Nature, 150, 405

Bavassano, B., & Bruno, R. 1989, J. Geophys. Res., 94, 168

Bavassano, B., Dobrowolny, M., Fanfoni, G., Mariani, F., & Ness, N. F. 1982, SoPh, 78, 373

Bavassano, B., Pietropaolo, E., & Bruno, R. 1999, in Am. Inst. Phys. Conf. Proc., Vol. 471, Solar Wind Nine, ed. S. R. Habbal, R. Esser, J. V. Hollweg, & P. A. Isenberg (College Park, Md.: Am. Inst. Phys.), 503–506

Bavassano, B., Pietropaolo, E., & Bruno, R. 2000a, J. Geophys. Res., 105, 12697

—. 2000b, J. Geophys. Res., 105, 15959

Belcher, J. W. 1971, ApJ, 168, 509

Belcher, J. W., & Davis, Jr., L. 1971, J. Geophys. Res., 76, 3534

Belcher, J. W., Davis, Jr., L., & Smith, E. J. 1969, J. Geophys. Res., 74, 2302

Bruno, R., Bavassano, B., & Villante, U. 1985, J. Geophys. Res., 90, 4373

Bruno, R., & Carbone, V. 2013, Living Rev. Solar Phys., 10, 2

Bruno, R., & Dobrowolny, M. 1986, Ann. Geophys., 4, 17

Burlaga, L. F., & Turner, J. M. 1976, J. Geophys. Res., 81, 73

Chao, J. K., Hsieh, W. C., Yang, L., & Lee, L. C. 2014, ApJ, 786, 149

Daily, W. D. 1973, J. Geophys. Res., 78, 2043

D'Amicis, R., & Bruno, R. 2015, ApJ, 805, 84

Denskat, K. U., & Burlaga, L. F. 1977, J. Geophys. Res., 82, 2693

Denskat, K. U., & Neubauer, F. M. 1982, J. Geophys. Res., 87, 2215

Denskat, K. U., Neubauer, F. M., & Schwenn, R. 1981, in Solar Wind 4, ed. H. Rosenbauer (Garching: Max Planck Institute für Aeronomie), 392

Dobrowolny, M., Mangeney, A., & Veltri, P. 1980, Phys. Rev. Lett., 45, 144

Ebert, R. W., Dayeh, M. A., Desai, M. I., McComas, D. J., & Pogorelov, N. V. 2013, ApJ, 768, 160

Goldstein, B. E., Smith, E. J., Balogh, A., et al. 1995, Geophys. Res. Lett., 22, 3393

Gosling, J. T., McComas, D. J., Roberts, D. A., & Skoug, R. M. 2009, ApJL, 695, L213

Gosling, J. T., Tian, H., & Phan, T. D. 2011, ApJL, 737, L35

Grappin, R., Mangeney, A., & Marsch, E. 1990, J. Geophys. Res., 95, 8197

Grappin, R., & Velli, M. 1996, J. Geophys. Res., 101, 425

He, J., Pei, Z., Wang, L., et al. 2015, ApJ, 805, 176

Hollweg, J. V. 1973a, ApJ, 181, 547

—. 1973b, J. Geophys. Res., 78, 3643

—. 1974, J. Geophys. Res., 79, 1539

Horbury, T. S., Balogh, A., Forsyth, R. J., & Smith, E. J. 1995, Geophys. Res. Lett., 22, 3401

Li, H., Wang, C., Belcher, J. W., He, J., & Richardson, J. D. 2016, ApJL, 824, L2

Marsch, E., & Tu, C. Y. 1990, J. Geophys. Res., 95, 8211

Matthaeus, W. H., & Goldstein, M. L. 1982, J. Geophys. Res., 87, 6011

Matthaeus, W. H., Minnie, J., Breech, B., et al. 2004, Geophys. Res. Lett., 31, 12803

McComas, D. J., Barraclough, B. L., Funsten, H. O., et al. 2000, J. Geophys. Res., 105, 10419

Neugebauer, M. 2004, J. Geophys. Res., 109, 2101

Riley, P., Sonett, C. P., Tsurutani, B. T., et al. 1996, J. Geophys. Res., 101, 19987

Roberts, D. A., Goldstein, M. L., & Klein, L. W. 1990, J. Geophys. Res., 95, 4203

Roberts, D. A., Goldstein, M. L., Klein, L. W., & Matthaeus, W. H. 1987a, J. Geophys. Res., 92, 12023

Roberts, D. A., Klein, L. W., Goldstein, M. L., & Matthaeus, W. H. 1987b, J. Geophys. Res., 92, 11021

Shi, M. J., Xiao, C. J., Li, Q. S., et al. 2015, ApJ, 815, 122

Smith, E. J., Balogh, A., Neugebauer, M., & McComas, D. 1995, Geophys. Res. Lett., 22, 3381

Smith, E. J., Neugebauer, M., Tsurutani, B. T., et al. 1997, Adv. Space Res., 20, 55

Tsurutani, B. T., Ho, C. M., Arballo, J. K., et al. 1996, J. Geophys. Res., 101, 11027

van der Holst, B., Sokolov, I. V., Meng, X., et al. 2014, ApJ, 782, 81

Villante, U. 1980, J. Geophys. Res., 85, 6869

Wang, X., Tu, C., Wang, L., He, J., & Marsch, E. 2015, Geophys. Res. Lett., 42, 3654

Wenzel, K. P., Marsden, R. G., Page, D. E., & Smith, E. J. 1992, A&AS, 92, 207

Whang, Y. C. 1973, J. Geophys. Res., 78, 7221

Yang, L., & Chao, J. K. 2013, Chin. J. Space Sci., 33, 353

Yang, L., Lee, L. C., Chao, J. K., et al. 2016, ApJ, 817, 178